JOINT HIGHWAY RESEARCH PROJECT

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DEVELOPMENT AND USE OF A
COMPUTER SIMULATION MODEL FOR
THE EVALUATION OF DESIGN AND
CONTROL ALTERNATIVES FOR
INTERSECTIONS OF MINOR ROADS
WITH MULTI-LANE RURAL HIGHWAYS:
MODEL APPLICATION

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Interim Report

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FOR THE EVALUATION OF DESIGN AND CONTROL ALTERNATIVES
FOR INTERSECTIONS OF MINOR ROADS WITH
MULTI-LANE RURAL HIGHWAYS: MODEL APPLICATION

TO: H. L. Michael, Director
Joint Highway Research Project

July 11, 1979

FROM: K. C. Sinha, Research Engineer
Joint Highway Research Project

Project: C-36-59X

File: 8-5-24

Attached is an Interim Report on the Indiana HPR Part II study entitled "Evaluation of Design and Control of Alternatives to Improve Safety of Intersections at Multi-Lane Rural Highways." It has been authored by Ahmed Essam Radwan, Kumares C. Sinha and Harold L. Michael.

This portion of the study reported here presents the details of the model application in evaluating design and control alternatives to improve safety and traffic operation at intersections of minor roads with multi-lane rural highways. It basically is a report on Task 11 of the approved Proposal for the study.

The report is forwarded for review, comment and acceptance as partial fulfillment of the objectives of the research.

Respectively submitted,

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MULTI-LANE RURAL HIGHWAYS: MODEL APPLICATION

by

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The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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EVALUATION OF COUNTERMEASURES
AT STOP CONTROLLED INTERSECTIONS

This report deals with the evaluation of design and operational countermeasures and their effects on safety and operation of the intersection of a four-lane major divided highway with a two-lane minor road controlled by a stop sign. The logic of the validated model made it possible to simulate traffic through divided intersections composed of a wide spectrum of geometrical design variables. Important variables which were suggested by multidisciplinary team studies and a correlation study on other phases of this project as well as others from the literature were: intersection median width, median opening, approach grades, and the existence of a right turn pocket lane on the minor road. In addition, only those countermeasures were considered which could be related to operational characteristics of an intersection.

The number of conflicts detected from the simulation model was assumed to be the measure of effectiveness for safety. As for the measure of effectiveness for traffic operation, the average delay per vehicle was used.

A detailed study was conducted to study the possible countermeasures by means of the simulation model. A wide range of possibilities was considered and the areas where possible changes can be made to improve safety and traffic operation are listed below:

1. The distance between the two stop lines on the minor road approaches representing the intersection width.
2. Median control.

3. Speed limit enforcement on minor roads.
4. The existence of advance warning systems such as advance warning sign, route markers, and rumble strips.

Five types of traffic conflicts, which the simulation model detects, take place at the intersection after the minor road vehicle has come to a complete stop. These types of conflicts are discussed in detail in an earlier Interim Report on this research project.

To study the effects of speed limit enforcement and advance warning systems on traffic safety, an additional safety measure was introduced. This new measure was defined to be the sum of the number of vehicles that approach the stop line of the minor road at a high speed and the number of vehicles that do not stop at the stop line. Modifications in the simulation logic was made to detect and count those vehicles that did not stop at the stop line. At the same time the model was adjusted to keep a record of those vehicles that had a speed of 20 feet per second or more at a distance of 5 feet from the stop line. The reason for choosing this value of approaching speed was that for a vehicle to stop within a distance of five feet under a deceleration rate of four feet per second per second, the initial speed of such a vehicle would have to be equal to or less than 20 feet per second.

In order to evaluate the list of design and operational countermeasures discussed earlier, a complete factorial model of the fixed effect types was considered. Selecting three levels for median width, two levels for median opening, two levels for median control, three levels for intersection width, two levels for right turn pocket lane,

three levels for turning percentages, five levels for grade configurations, four levels for advance warning system, and two levels for speed limit enforcement, a total of 8640 data points would have been required for only one level of major-minor volume combination. Knowing that the average cost of simulating traffic through divided intersections for a time period of 400 seconds is around \$4.0, an experiment like this would have cost a total of \$33,560. One way of reducing the number of required data points was by assuming that three or higher factor interactions are negligible. Consequently, it was decided to perform the analysis in a group of small experiments of one, two, and three factors at the most per experiment. Because of the lack of information in the literature concerning the significance of the interaction of these variables, it was decided to combine some of the variables. The analysis of variance statistical test was used. The experiment number, variables for each experiment, and the levels of each variable are shown in Table 1 for unsignalized intersections.

Experiment 1: Evaluation of Intersection Median Width

This experiment was designed for the purpose of evaluating the effect of the median width of divided intersections and its impact on traffic safety and operation. To simulate traffic through divided intersections using the UTCS model, it was assumed that such an intersection consisted of two separate intersections, each with two-lane one-way traffic. A short link between them represented the intersection median. The length of this intermediate link was given a lower limit value equal to a vehicle length. It was assumed the average passenger car length was 20 feet and average truck length was 30 feet. Therefore

Table 1. Layout of the Five Experiments for Unsignalized Intersections

<u>Experiment Number</u>	<u>Variables</u>	<u>Levels</u>
1	Major Volume (vph) Minor Volume (vph) Median Width (feet)	200, 350, 500, 650, 800 50, 100 30, 60
2	Median Opening (feet) Right-Turn pocket (vehicles) Left-Turn, Through, Right-Turn	24, 48 0, 1 (10-80-10), (15-70-15), (20-60-20)
3	Approach Grades %	<div>MAJOR</div> <div>MINOR</div> <div>5% </div> <div>5% </div> <div>5% </div> <div>5% </div> <div>5% </div> <div>5% </div> <div>5% </div> <div>5% </div> <div>5% </div> <div>5% </div>
4	Median Control Intersection Width (feet)	Stop, Yield 108, 132, 156
5	Advance Warning System distance (feet) on minor approach Speed Limit Enforcement on minor (mph)	400, 800, 1200, 1600 35, 25

the minimum median width which allows at least one truck to stop was taken to be 30 feet. The higher levels of this variable can thus be in the multiples of 30 feet; such as 60 feet which allow 3 passenger cars or 2 trucks at the median.

The major road volume has a direct effect on the time gaps created on the major road, therefore by changing its levels the expected number of right-angle conflicts would change and in turn change the total number of conflicts. Variation in minor road volume may cause longer or shorter queues at both the stop sign of the minor road and the intersection median, therefore the interaction of median width and minor road volume was also thought to have significant effect on conflicts.

Five major volumes of 200, 350, 500, 650, and 800 vph and two minor volumes of 50 and 100 vph were considered. These volume levels were chosen to cover the possible flow rate ranges of stop control intersections. All the other factors were fixed during the experiment and they represented a hypothetical intersection:

1. Left turn, through, and right turn percentages for the major road traffic were 5, 90, and 5, respectively.
2. Left turn, through, and right turn percentages for the minor road were 15, 70, and 15, respectively.
3. Truck percentages were assumed 30 percent of the major traffic and 10 percent of the minor traffic.
4. Intersection median opening of 48 feet which allows two lanes of traffic for each direction.
5. Low grades were considered for both major and minor approaches.

Each cell, representing a particular major volume-minor volume median width combination, was simulated by the model for a 600 second simulation duration. Since modeling random events and human behavior requires access to many probability distributions, a number of repeated runs was required to derive an adequate sample estimate for the true population mean for each cell. Each cell stored the average dependent value for the variables: 1. Average delay per vehicle (seconds), 2. Number of conflicts, 3. Stop delay per vehicle (seconds), 4. Delay per vehicle-mile of travel (minutes per vehicle-miles), 5. Minor road delay (seconds), 6. Major road delay (seconds). The six response measures were simultaneously obtained for each cell. An analysis of variance model, shown in Table 2, indicated that three replicated runs per cell provided an adequate estimate of the residual error. The effect of major road volume, minor road volume, and median width were all tested by the error term in the model. Also the interaction of two out of the three variables as well as the interaction of all the three variables were tested by the error term. The linear model was formulated with the assumptions of homogeneity of variances, normality, additivity, and independence of errors.

The three replicate entries in each cell, after demonstrating satisfaction of the W-test for normality and the Burr-Foster Q-test for variance homogeneity, were subjected to analysis of variance procedure. This analysis of variance statistical test was conducted for each dependent variable. It was found that the three factor interaction (major volume, minor volume, median width) was significant for the case of conflicts at level of significance $\alpha = .05$ and the other

Table 2. The Statistical Model of Experiment 1

Model

$$Y_{ijkl} = \mu + A_i + B_j + AB_{ij} + C_k + AC_{ik} + BC_{jk} + ABC_{ijk} + \epsilon_{(ijk)\ell}$$

ANOVA: (3 replicates per cell)

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Expected Mean Square</u>
A_i	4	$\sigma^2 + 12 \phi_A$
B_j	1	$\sigma^2 + 30 \phi_B$
AB_{ij}	4	$\sigma^2 + 6 \phi_{AB}$
C_k	1	$\sigma^2 + 30 \phi_C$
AC_{ik}	4	$\sigma^2 + 6 \phi_{AC}$
BC_{jk}	1	$\sigma^2 + 15 \phi_{BC}$
ABC_{ijk}	4	$\sigma^2 + 3 \phi_{ABC}$
Within Error	40	σ^2
Total	59	

where

A_i = major volume per approach $i = 1, 2, 3, 4, 5$

B_j = minor volume per approach $j = 1, 2$

C_k = median width $k = 1, 2$

Y_{ijk} = estimated dependent variable: delay, fuel consumption, and conflicts

$\epsilon_{(ijk)}$ = random error component

σ^2 = random variance

ϕ_z = variance contributed by a fixed factor where z = major volume, minor volume, and median width

ℓ = 3, number of replicates per cell

μ = overall mean

dependent variables were not significant. Results of the ANOVA are shown in Tables A-1, A-2, A-3, A-4, A-5, and A-6, Appendix A. It was found that both major and minor volumes have a significant effect on all dependent variables, except in the case of minor road delay, for level of significance $\alpha = .05$. Minor road delays were found to be significantly affected by major volume, however minor volumes were not affecting it for level of $\alpha = .05$. Median width was found not to have any significant effect on both delay and conflict. On the other hand, the three factor interaction showed significance for the case of conflicts at level of significance $\alpha = .05$ and hence a multiple comparison test was considered. A modified version of the student Newman-Keuls technique was applied to compare the means of the three factor interaction. Twenty cells were studied-each contained the mean value of three replicates. A summary of the significant differences between the means is shown in Table A-7, Appendix A. Comparisons of the individual means of the three replicates for the three factor interaction revealed the following:

1. At major volume of 800 vph, minor volume of 50 vph and median width of 30 feet, the number of conflicts was significantly higher than the number of conflicts for the six cases of the combination of the two major volumes 200, 350 vph, the two minor volumes 50 and 100 vph, and the two median widths 30 and 60 feet.
2. The interaction of major volume 500 vph, minor volume 50 vph, and median width 60 feet had a significantly higher number of conflicts than the six cases mentioned above.

3. As for the case of major volume of 650 vph, minor volume 50 vph and median width 30 feet, the number of conflicts was significantly higher than the case of major volume 200 vph, minor volume 50 vph, and median width 60 feet as well as the case of major volume 350 vph, minor volume 100 vph, and median width 30 feet.

The means of the twenty cells of this experiment were plotted in Figure 1 to show the effect of major volume, minor volume, and median width on average delay and conflicts.

The following observations were made on the basic results of this experiment:

1. All the seven delay measurements were significantly affected by traffic flow on both major and minor roads. This result confirmed the consistency of the model for estimating delay at intersections. Therefore it was decided to use only the average delay per vehicle in the following experiments as the traffic operational measure.
2. Both major and minor road volume had a significant effect on conflicts, a conclusion which supported the consistency of the model in predicting conflicts.
3. At high major road volumes and median width of 30 feet, the number of conflicts was significantly higher than any other combination. As the median width increased, the number of conflicts decreased.

The overall conclusion reached from this experiment was that the median width of a divided highway should be chosen sufficiently large

FIGURE 1, EFFECT OF MAJOR VOLUME, MINOR VOLUME, AND MEDIAN WIDTH ON AVERAGE DELAY AND CONFLICTS

enough at the early stages of the planning process. A question can be raised concerning this subject: What will happen to traffic delay and safety if the median width is less than 30 feet? Median width values less than 20 feet do not provide protection either for passenger cars or for trucks. On the other hand, median width values larger than 20 feet and less than 30 feet will cause truck drivers to over-hang the rear-end of their vehicles exposed to the major road traffic which is a potential hazard. From the previous discussion, it was decided to assume that all possible median width values less than 30 feet are represented by the undivided intersection case.

Traffic delay comparisons between divided and undivided intersections were discussed in an earlier interim report on this project. As for safety, a group of simulation runs were implemented to predict number of conflicts occurring at unsignalized intersections. The purpose of these runs was to compare the undivided case against the 30 foot median width case. Four levels of major road volumes 350, 500, 650, and 800 vph and two levels of minor road volumes 50 and 100 vph were investigated. Three simulation replications, each 400 seconds duration, were run for each major-minor road volume combination. The other geometrical and operational factors were kept the same as those of experiment 1. Because the simulation duration of the 30 foot median width case (600 seconds) was different than that of the zero foot median width case (400 seconds), conflict rates were used in the analysis instead of number of conflicts. Conflict rates were calculated by dividing total number of conflicts by the sum of traffic volume entering the intersection from both major and minor approaches during the simulation period.

Homogeneity and normality tests were checked and no transformation was needed. A statistical analysis of variance test was performed and the results of this test, shown in Table A-8, Appendix A, indicated that major volume, minor volume and median width and their possible interactions are significant at level of $\alpha = .05$. The Newman-Keuls test was applied on the cell means of the three factor interaction and it was concluded that the conflict rate of the case of major road volume 500 vph, minor road volume 50 vph, and undivided intersection were found to cause the highest conflict rates and the differences between this rate and all other rates were significant at α level of .01. The implications of these findings are the following: At major road volume of 500 vph the average time gap is approximately 7.2 seconds and this average value varies from 11.0 seconds, at a flow rate of 200 vph, to 4.50 seconds at a flow rate of 800 vph. Therefore, the probability of a minor road vehicle to accept a medium (7.2 seconds) or large size gap (11.0 seconds) in the major flow is higher than the probability of accepting a small size gap (4.5 seconds). On the other hand, the evasive actions of major road drivers due to minor road vehicle interruption, such as lane changing or braking, are more frequent at medium traffic volumes than at low volumes. Hence the number of conflicts occurring at medium traffic volumes (500 vph) are probably higher than those of small (200 vph) and large volumes (800 vph).

It was also noted from the simulation results that conflict rates for undivided intersections (zero median width) were larger than those for the intersection with 30 foot median width, a result which can be expected because of the fact that minor road drivers on undivided intersections are required to perform their maneuvers in one

movement without stopping at the median and therefore they tend to accept unsafe gaps. This conclusion complements the results of experiment 1 which indicated that the increase in median width causes an increase in number of conflicts.

Experiment 2: Width of Median Opening and the Provision of Right Turn Pocket Lane

The purpose of this experiment was to study the effect of the width of median opening and the existence of right turn pocket on delay, and conflicts at intersections. Two levels of median openings were considered. A 24 foot median opening which allows one lane of traffic per direction and a 48 foot for two lanes per direction. The second variable was the existence of a right turn pocket lane on the minor road with a capacity of two vehicles. The interaction between the two variables mentioned above and the turning and through volumes of the minor road were thought to have a significant effect on both traffic operation and safety. Therefore it was decided to include a third independent factor in the experiment which represented the percentage of turning movement traffic. Three levels of 10-80-10, 15-70-15, and 20-60-20 were studied for left turn-through movement-right turn percentages, respectively. A typical intersection was considered with the following characteristics:

1. Major road volume of 600 vph and a minor road volume of 100 vph.
2. Truck traffic of 30 and 10 percent for major and minor volumes.
3. Median width of 30 feet.
4. Stop sign at median.

A linear model of complete randomized design with a fixed factor, similar to the model shown in Table 2 was used to analyze this experiment. The design led to 12 cells each stored three replications. Two dependent variables were obtained from the simulation runs and they were:

1. Average delay per vehicle (seconds)
2. Number of conflicts.

The test of homogeneity (Burr-Foster) and the normality test (W-test) were satisfied for this experiment. The analysis of variance procedure was implemented for the two dependent variables and it was found that the turning movement percentages, and the existence of right turning pocket lane on the minor road had no significant effect on either average delay or on number of conflicts. As for the effect of width of median opening, it was found to be significant for average delay per vehicle and not significant for number of conflicts, for α level of .05. The results of ANOVA for average delay and number of conflicts, are shown in Tables A-9 and A-10, Appendix A.

The results of this experiment suggest that median openings should have enough width to allow two lanes of traffic per direction to reduce delay and improve traffic operation. The provision of a right turn pocket lane was proved not to provide any significant improvement in traffic safety and operation. It should be pointed out that the results of this experiment are valid only to the type of intersections considered in the analysis.

Experiment 3: Evaluation of Roadway Gradients

The effect of roadway gradient on traffic safety and operation was incorporated into the simulation exercise in two separate ways. The first involves the specification of the average intersection discharge rate and the second approach concerns the performance of trucks along links with significant grades.

The UTCS simulation model uses one set of acceleration rates for all passenger cars. This rate is 8 ft/sec^2 until the vehicle reaches the speed of 16 ft/sec; thereafter, the acceleration rate is 3 ft/sec^2 until the speed assigned to the vehicle is attained. The logic of the model assumes that the acceleration rate and speed characteristics are not significantly affected by grades because of the high performance characteristics of passenger cars. Acceleration rates for trucks under all conditions were specified as 3 ft/sec^2 until the vehicle reaches the speed of 16 ft/sec when the acceleration rate was reduced to 2 ft/sec^2 .

In order to implement experiment 3, a group of simulation runs was made, in which different roadway gradients on both major and minor approaches were considered. Negative or positive grades on each approach and/or both approaches were considered for minor road as well as major road and the combinations of these gradient alternatives amounted to five patterns both positive and negative cases. Three computer replications of 480 seconds of simulation period for each pattern were studied under major traffic volume of 800 vph and minor traffic volume of 100 vph. These volumes were chosen as they are the threshold values beyond which signalization is generally warranted.

Three dependent variables were considered: 1. Average delay per vehicle, 2. Stop delay per vehicle, 3. Number of traffic conflicts. The five design alternatives and the average cell values of the dependent variables can be seen in Table 3. The cell means of the first four alternatives were noticed to be very close and smaller than the cell mean of the fifth alternative. The same phenomenon was observed for stop delay per vehicle and the reason for the increase in delay is probably because the high speed of major road traffic approaching the intersection on downgrade causes minor road vehicles to wait longer for the purpose of finding an acceptable gap.

The highest number of traffic conflicts was also observed from the fifth alternative, a result which was expected because right turn and left turn minor road vehicles require long distance on the upgrade major road approach to attain the free-flow speed of that link, and consequently more "brake light" and "lane switch" conflicts occur. On the other hand, the lowest number of conflicts were observed from the opposite design configurations in which major road vehicles approach the intersection on an upgrade and leave it on downgrade. Statistical homogeneity and normality tests were checked and no transformation was needed for the variable "number of conflicts". A Napierian logarithm transformation was performed on both delay variables to make the variances of all cells equal for level of significance $\alpha = .05$. A one-way analysis of variance was conducted for the three dependent variables and the analysis showed significance for the conflict variable at α level of .05; however, the two delay variables were found to be nonsignificant. The results of the statistical analysis are summarized in Table A-11, Appendix A.

Table 3. Roadway Gradient Alternatives and Their Effect on Delay and Conflicts for Experiment 3

Alternative Number	Major Road Grades	Minor Road Grades	Average Delay Per Vehicle	Stop Delay Per Vehicle	Number of Conflicts
1	$\leq + 5\%$	$\leq + 5\%$	24.050	7.203	4.666
2	$\leq + 5\%$	$\leq + 5\%$	24.026	4.313	5.000
3	$\leq + 5\%$	$\leq + 5\%$	26.816	7.376	3.666
4	$\leq + 5\%$	$\leq + 5\%$	25.016	6.443	8.666
5	$\leq + 5\%$	$\leq + 5\%$	33.576	13.583	11.333

On the basis of the results of this experiment it can be stated that the last two design alternatives, as shown in Table 3, are not conducive to safety at divided highway intersections.

Experiment 4: Evaluation of Median Control and Intersection Width

Yield and stop controls were considered as median control variables and three intersection widths of 108, 132, and 156 feet for the second variable. A complete randomized linear model, of fixed factor type, was adopted for this experiment. Three replicates per cell were obtained from the computer simulation runs. The within error term was used to test the effect of median control, the intersection width, and their interaction which can be observed from Table A-12, Appendix A. A typical intersection with the following geometrical and operational factors was considered.

1. Minor and major volume were assumed to be 100 vph and 800 vph.
2. Major road turning percentages were 5, 90, and 5, and minor road turning percentages were 40, 30, and 40 for left turn, through movement, and right turn, respectively.
3. Median width of 30 feet and width of median opening of 48 feet.
4. A left-turn pocket lane on the major road with a capacity of four vehicles and a right-turn pocket lane with a capacity of two vehicles on the minor approach.
5. Major road truck traffic of 30 percent, and minor road of 10 percent.

Average delay per vehicle and number of conflicts were obtained from the simulation runs. The ANOVA results showed that median control

had a significant effect on the number of conflicts for α level of .05. Summary of the ANOVA results for average delay per vehicle and number of conflicts are shown in Tables A-13 and A-14, Appendix A. The mean response of the six cells of this experiment were plotted and they are shown in Figure 2. The two plots of Figure 2 indicate that using stop control at the intersection median causes less conflicts than installing yield control and this reduction was proved to be significant from ANOVA. This experiment concluded that by installing a positive control device at the intersection median, such as stop sign or flasher as opposed to yield sign or no control, safety is improved significantly. This conclusion is true because the installation of a stop sign at the median causes all minor road vehicles to come to a complete stop at the median before crossing or merging with the major road traffic in the simulation model and a second gap acceptance value is then assigned to the driver. This gap size varies depending upon the driver type, and a "brake light" or "lane switch" conflict may or may not take place on the major road approaches. On the other hand, the installation of a yield sign at the median allows drivers to perform their maneuvers at a speed of 10 mph in the program; therefore the probability of major road conflict occurrence is higher than that for stop control.

Experiment 5: Evaluation of Advance Warning Systems and Speed Enforcement

The advance warning systems included advance warning signs, rumble strips, and route markers located on the minor approach.

The simulation logic involving the minor vehicle movement on an intersection approach is determined by the following two variables:

FIGURE 2, EFFECT OF CONTROL TYPE AT MEDIAN AND INTERSECTION WIDTH ON AVERAGE DELAY AND NUMBER OF CONFLICTS

1. The distance between the position of the vehicle and the downstream node of the minor road link, 2. The distance required for a vehicle to come to a complete stop with a rate of deceleration of 7 feet per second per second which is the safe stopping distance. The process of reducing the speed of a vehicle starts when the distance between this vehicle and the stop line becomes equal to or less than the safe stopping distance. The distance between the vehicle and the stop line is a function of the length of the link in which the vehicle is located; therefore the sight distance of a vehicle is indirectly represented by the length of intersection approaches. By varying this length, the evaluation of advance control systems becomes possible.

As for speed enforcement it was decided to vary the target speed of minor road links in the simulation model and study its effect on conflicts and delays.

Three measures of effectiveness were observed from the simulation runs and they were:

1. Number of conflicts as defined earlier in Interim Report 4 (1).
2. The Number of vehicles that passed the stopping line or have an approaching speed higher than 20 feet per second.
3. The average delay per vehicle.

Before setting up possible levels of advance warning systems, it was decided to consult previous researches. In an early study, Kermit (2) observed that the use of rumble strips as an advance warning system at stop controlled intersections caused marked changes in driver behavior and substantial savings in accident cost. The results of this study showed that, on the average, the reduction of vehicle

speed was 9 mph, observed at a location 450 feet away from the intersection, after three rumble strips were crossed. The first of the three rumble strips was located 1000 feet away from the intersection.

Visual transmission by means of signs, as opposed to audible stimuli produced by rumble strips, was a natural development. However, early signs were varied and often difficult to read, Forbes (3) adopted the term "legibility" to indicate the ability to read the letters on a sign. A method for determining legibility distances for a standard block-letter alphabet was developed by him. In another study, the legibility distance was observed to vary from 200 feet to 2000 feet depending on light conditions, letter types, and letter heights (4).

A recent study by Ruden et. al. (5) evaluated the effect of strobe lights attached to advance warning signs on driver behavior at rail-road crossings. It was found from this study that advance warning signs without strobe lights did not cause drivers to reduce their speeds; the average speed observed at a distance of 500 feet away from the crossing was not significantly different from that observed at a distance of 2200 feet. On the other hand, attaching strobe lights on advance warning signs caused a reduction in speed of 15 mph as compared with the original condition.

Accordingly, four levels of 400, 800, 1200 and 1600 feet were considered for the advance warning system variable. As for the second independent variable, target speeds of 35 and 25 mph were assumed to be the appropriate levels. Three replicates per cell were observed and a linear model similar to the one used in experiment 4 was adopted to

perform the analysis of variance. Homogeneity and normality tests were satisfied and the ANOVA results are shown in Tables A-15, A-16, and A-17, Appendix A, for number of conflicts, number of vehicles exceeding safe speed (20 ft/sec), and average delay per vehicle, respectively. The cell means were plotted for the three dependent variables and they are shown in Figure 3.

The results of ANOVA showed that the advance warning system had a significant effect on average delay per vehicle as well as on number of conflicts. In Figure 3 it can be seen that as the advance warning distance increases, the number of conflicts decreases, and the average delay per vehicle increases. It can therefore be stated that the installation of an advance warning system at minor road approaches improves safety considerably. It was also concluded that speed enforcement on the minor road approaches did not have any significant effect on traffic delay and safety. The number of vehicles exceeding safe speeds was observed not to be affected by the two independent variables and the second plot of Figure 3 did not show any trend. It was concluded that this variable was not a good measure for safety evaluation and the other measure, number of conflicts, was sufficient for this experiment.

Some general conclusions were reached from this experiment and they were:

1. To improve safety at stop controlled intersections, advance warning systems can be installed in advance on the minor road approaches.

FIGURE 3 EFFECT OF TARGET SPEED AND ADVANCE WARNING DISTANCE ON CONFLICTS, NUMBER OF VEHICLES EXCEEDING SAFE SPEED, AND AVERAGE DELAY

2. Speed enforcement at minor road approaches, as evaluated by the simulation model, proved to have no significant effect on traffic safety.
3. Measure of effectiveness of number of vehicles exceeding safe speed proved to be inefficient to evaluate safety at stop-controlled intersections.

EVALUATION OF COUNTERMEASURES AT SIGNALIZED INTERSECTIONS

The dominant types of accidents at signalized intersections are the following: 1. Rear end accidents caused by drivers who fail to stop for slowing or stopped vehicles turning right or left or stopped on amber or red, 2. Right angle accidents created by vehicles who ran a red light, or entered the intersection during a short amber phase, 3. Left turning accidents caused by drivers who accept an unsafe gap in the opposing traffic to perform a left turning maneuver.

For the signalized intersections the measure of effectiveness of the safety aspect was represented by the sum of the number of vehicles stopped at the intersection and the number of vehicles which go through the intersection during the amber phase. This measure was used to evaluate the first two types of accidents. For the third type of accidents the safety was evaluated by the number of vehicles that accept a gap shorter than a 5-second gap size. An in-depth study of the possible areas in which an improvement of safety can be made at signalized intersections, including the interdisciplinary team and correlation studies of this research, yielded the following list:

1. Type of control alternatives such as fixed time signal, semi-actuated, fully actuated, volume-density control, and green-extension system (GES).

2. Signal timing.
3. Advance warning systems such as rumble strips, advance warning signs, and route markers located on minor approaches.
4. Number of signal phases.
5. Duration of amber and all-red phase.
6. Speed enforcement on major roads.
7. Locations of detectors for the actuated control units.

Each of the above variables was evaluated through the application of the computer model as discussed in the following sections.

Experiment 6: Evaluation of Control Alternatives

Five signal control systems were studied, each with two phases and their signal timings were as follows:

1. Fixed-time signal with a total cycle length of 80 seconds where the duration of the two phases are proportioned with the volume of traffic on both approaches.
2. Semi-actuated control with initial interval of 12 seconds, vehicle extension of 3 seconds, and maximum extension of 24 seconds for the actuated phase of the minor approach. A minimum green interval of 36 seconds was adopted for the major approach (non actuated).
3. Fully-actuated control with an initial interval of 12 seconds, a vehicle extension of 3 seconds, and a maximum extension of 27 seconds for the minor road approach. These values were 16, 4, and 64 seconds respectively for the major road approach.

4. Fully-actuated control unit similar to the one mentioned above and provided with variable initial interval and gap reduction feature (Volume-Density Control). A maximum initial interval of 24 seconds, number of actuations to reach maximum of 8, a minimum gap of 8 seconds, and a maximum gap of 10 seconds was used for the major approach. These values were 12, 6, 6, and 10 respectively for the minor road approach. The values of initial interval, vehicle extension and maximum extension were assumed to be 12, 4, and 60 for major approach, and 6, 4, and 34 for minor road approach.
5. A green extension system (GES) is a fully actuated control with more than one loop detector on the major road to detect the approaching vehicle in advance and extend the green phase duration on the major link. The extension of the green phase reduces the probability of a vehicle getting trapped in the dilemma zone when the signal turns amber. For this control type a maximum extension of 90 seconds was used on the major approach with a passage time of 5 seconds and an initial interval of 15 seconds. As for the minor approach, the same figures used in the previous control alternative were assumed. The signal timings of the five controls were chosen to be the average of the upper and lower boundaries suggested by the Southern Section of the Institute of Traffic Engineers (SSITE) (6).

All the five control alternatives had an amber phase of 4 seconds, a major volume of 800 vph, a minor volume of 100 vph and turning percentages of 5, 90, and 5 for left turn, through, and right turn movements

on the major approach. Three replicates each of 400 seconds were considered for each alternative. Number of vehicles stopped during amber phase, number of vehicles continuing during the amber phase, and average delay per vehicle were observed from the simulation output. The total number of the first two variables was called "number of conflicts". Homogeneity of variances and normality test were satisfied and a one-way analysis of variance was conducted for both dependent variables. The results of ANOVA showed that there was no significant difference between the number of conflicts observed for the five control alternatives, however the average delay per vehicle was found to be significantly different at level $\alpha = .05$. The cell means and the ANOVA results can be seen in Table A-18, Appendix A. Although not found to be statistically significant at $\alpha = .05$, it was noticed that fixed-time and semi-actuated controls cause more conflicts than fully actuated, volume density and GES controls. This is explained by the fact that the number of amber phases for the first two alternatives are higher than the last three; more amber phases increase the probability of hazardous conditions at an intersection. On the other hand, the average delay per vehicle for these two alternatives are smaller than the values observed for the other three control alternatives.

Experiment 7: Effect of Signal Timing on Conflicts and Delay

The previous experiment showed that the control type had no significant effect on number of conflicts, therefore it was decided to consider only one control type for the next experiment. Consequently the experiment to test the effect of signal timing was conducted with the

fully-actuated control. Three independent variables were set up and they were: 1. Major road volume of 400, 800, and 1200 vehicles per hour, 2. Minor road volume of 100 and 300 vehicles per hour, 3. Maximum green extension periods of 36, 48, and 60 seconds for major road and the corresponding values for minor road were 18, 26, and 34 seconds, respectively. For this experiment it was necessary to determine the interaction of signal timing with the major road and minor road volumes and this was accomplished by using the error term. Geometrical and operational aspects were kept constant for all simulation runs. An initial interval of 12 seconds, and a vehicle extension of 4 seconds were used for the major road. These values were 6 and 4 seconds for the minor approach. Major road turning percentages were 5, 90, and 5, and minor road percentages were 30, 40, 30 for left turn, through, and right turn, respectively. Four percent commercial traffic was assumed for minor approach and six percent for major approach. An elapsed simulation time of 450 seconds was considered for each case. Three dependent variables were observed from the simulation runs and they were: 1. Average delay per vehicle, 2. Total number of conflicts, 3. Left turn conflicts. Analysis of variance test results are shown in Tables A-19, A-20, and A-21, Appendix A.

The results of ANOVA showed that both minor and major road volumes significantly affect average delay per vehicle for significance level of $\alpha = .05$. As for number of conflicts, major volume was found to have significant effect at α level of .05. Both minor road volume and signal timing showed significant effect on left turn conflicts at $\alpha = .05$. In addition, the following results were reached: 1. The combination of

the major and minor road volumes significantly affect the average delay per vehicle at $\alpha = .05$, 2. The combination of the minor volume and signal timing significantly affect left turning conflicts at $\alpha = .05$. Therefore, a multiple comparison test was performed to find the levels which had the significant effect. Newman-Keuls test was conducted on the means of the significant two-factor interactions including their main effects and the results are shown in Tables A-22 and A-23, Appendix A. The results of Table A-22 showed that the three major-minor volume interactions (1200x300), (1200x100), and (800x300) have average delay significantly higher than all other interactions at a level of significance $\alpha = .01$. As for the minor volume-signal timing interaction, it was found that the case of minor volume 300 vph, maximum extension green interval for major road of 60 seconds, and maximum extension green interval for minor road of 34 seconds have left turn conflicts significantly higher than all other cases for α level of .05.

The cell means were plotted for the purpose of observing the effect of the three independent variables on average delay per vehicle, number of conflicts, and left turn conflicts and these plots are shown in Figures 4 and 5. The results of ANOVA and plots of the cell means revealed the following:

1. Major and minor road volumes and their interactions have a significant effect on delay. Also it was observed that traffic volume and average delay per vehicle are positively correlated.
2. Both major and minor road volumes are negatively correlated with number of conflicts. As the maximum green extension increases the number of conflicts decrease.

FIGURE 4, EFFECT OF MAJOR VOLUME, MINOR VOLUME, AND SIGNAL TIMING ON AVERAGE DELAY PER VEHICLE

FIGURE 5, EFFECT OF MAJOR VOLUME, MINOR VOLUME, SIGNAL TIMING ON NUMBER OF CONFLICTS AND LEFT TURN CONFLICTS

Maximum extension was found to affect significantly the number of conflicts occurring at a signalized intersection; this suggests that one should maximize the green extension phase on both approaches to minimize conflicts and improve safety.

3. Signal timing and minor road volume were found to have significant effect on left turn conflicts and major road volume was not significant for level $\alpha = .05$.

Experiment 8: Effect of Advance Warning System and Separate Left Turn Phase on Traffic Safety and Operation

The purpose of this experiment was to study the effect of the following factors on delay and conflicts at intersections:

1. Advance warning system on both major and minor approaches.
2. Adding a separate left turn phase to the control unit.

A fully-actuated control was adopted for this experiment with an initial interval period of 12 seconds, vehicle extension of 4 seconds, and maximum extension of 60 seconds for major road and values of 6, 4, and 34 seconds for minor road. The major and minor road volumes were fixed at arbitrary values of 1000 and 150 vph. Turning movement percentages were assumed to be 15, 80, 5 percent for left turn, through, and right turn maneuvers, respectively, of major road, and 30, 40, and 30 percent for minor road. Commercial traffic was assumed to be 30 and 10 percent for major and minor traffic, respectively.

To study the effect of advance warning system on traffic performance, three different conditions for the location of such warning were considered:

1. Distances of advance warning system from the stop lines of major and minor approaches were 500 and 300 feet, respectively.
2. Distances of advance warning system from the stop lines of major and minor approaches were 1000 and 600 feet, respectively.
3. Distances of advance warning system from the stop lines of major and minor approaches were 1500 and 900 feet, respectively.

As for the separate left turn phase, a third phase of initial interval equal to 6 seconds, vehicle extension equal to 3 seconds, and maximum extension equal to 18 seconds, was used. Three replicates per cell were simulated with a simulation period of 450 seconds and a linear model of a fixed effect type was adopted to calculate the ANOVA for this experiment. The results of ANOVA showed that the distance of the advance warning system from the stop line as well as the addition of a separate left turn phase did not have a significant effect on traffic safety and operation. Also the two factor interaction of the two variables mentioned above proved to have no significant effect on traffic characteristics. Number of conflicts, number of vehicles exceeding safe speed, and number of left turn conflicts were chosen as safety measures. As for traffic operation, the average delay per vehicle was adopted as a measure of effectiveness.

The results of ANOVA are shown in Tables A-24, A-25, A-26, and A-27, Appendix A. In addition, the cell means are plotted in Figure 6. The plots indicate that an addition of a separate left turn phase reduces the number of left turn conflicts but increases the average delay per vehicle. The reduction of left turn conflicts was proved, by ANOVA, not to be significant at $\alpha = .05$.

	LEVELS	MAJOR	MINOR
DISTANCE OF ADVANCE	1	500 feet	300 feet
WARNING SYSTEM	2	1000feet	600 feet
FROM STOP LINE	3	1500 feet	900 feet

FIGURE 6, EFFECT OF NUMBER OF PHASES AND DISTANCE OF ADVANCE WARNING SYSTEM ON SAFETY AND OPERATION OF TRAFFIC

The results of this experiment indicated that the location of the advance warning system at signalized intersections did have an effect in decreasing the number of observed conflicts, however the decrease was not significant at $\alpha = .05$. The measure "Number of vehicles exceeding safe speed" was found to be inconsistent with the change in the location of the advance warning system and led to the rejection of this measure as a variable in evaluating advance warning countermeasures for both signalized and unsignalized intersections.

Left-Turn Accidents Caused by Shadow Factor

The simulation model was modified to incorporate the occurrence of possible conflicts created by the shadow factor of left turning vehicles. The logic of detecting such conflicts was explained in Interim Report 4 (1). Several computer runs were performed with different traffic volumes and it was noticed that such situations occurred rarely. Therefore, it was decided to use a probabilistic approach for evaluating this type of accident. The conditional probability of the shadow factor conflict is shown in equation 1.

$$\begin{aligned}
 P(\text{shadow factor conflict}) &= P(\text{a vehicle making a left turn}) \times \\
 &P(\text{a vehicle making left turn from the opposite approach}) \times \\
 &P(\text{at least one or more opposing vehicles going through the} \\
 &\quad \text{intersection})
 \end{aligned}
 \tag{1}$$

The multiplication of the second and third terms of equation 1 represents a left-turn conflict.

A left-turn conflict is defined as the simultaneous existence of a left turn and an opposing through vehicle, both on the major road, within a time period Δt in seconds. As this time period decreases the probability of having a left-turn accident increases. The time gap Δt at which a left-turn accident occurs was called "critical gap".

The probability of a left-turn conflict is equal to the probability of at least one or more opposing vehicles going through the intersection within the critical gap and at least one vehicle wants to turn left. This is known as the conditional probability of any two events. Since the two events of this process, left-turn and through maneuvers, are mutually exclusive, the left-turn probability amounts to the multiplication of the probabilities of the individual events as shown in equation 2.

$$\text{Probability (left-turn conflict)} = P(A/B) = P(A) P(B) \quad 2$$

where, $P(A) = P(\text{at least one opposing vehicle is going through in } \Delta t)$.

$$P(B) = P(\text{at least one vehicle is turning left in } \Delta t).$$

Assuming that traffic flow follows a Poisson distribution, the individual probability terms can be seen in equations 3 and 4.

$$P(A) = 1 - P(\text{no opposing vehicle going through}) = 1 - e^{-\lambda_1 \Delta t} \quad 3$$

$$P(B) = 1 - P(\text{no vehicle turning left}) = 1 - e^{-\lambda_2 \Delta t} \quad 4$$

where, λ_1 = hourly opposing through movement rate/3600.

λ_2 = hourly left-turn rate/3600.

Knowing the probability of both maneuvers, the expected number of conflicts can be estimated from equation 5.

$$\text{Expected Number of Conflicts} = (1 - e^{-\lambda_1(\Delta t)}) (1 - e^{-\lambda_2(\Delta t)}) (\lambda_1 + \lambda_2) \quad 5$$

To be able to use equation 5 for conflict prediction purposes, one should estimate the critical gap, Δt . It has been established from a comprehensive study by the Federal Highway Administration (7) that approximately 15 left-turn accidents occur for every 100,000 left-turn conflicts. Knowing the number of reported accidents at a signalized intersection; the flow rates (λ_1 , λ_2); and the conflict to accident ratio, the critical gap Δt can be calculated. Therefore, the number of left-turn accidents reported for eight signalized intersections in Indiana were collected for the years 1974, 1975 and 1976. In addition, the average daily traffic figures for both opposing through and left-turn maneuvers were gathered for the same time period. The average critical gap values for the eight intersections were then calculated from equation 5 and they are shown in Table 4. A linear regression model was developed to estimate critical gap as a function of the average daily traffic for both maneuvers. A high correlation coefficient (r) of .947 and a significance α value of .003 for the regression term were attained.

Substituting the expression of a left-turn conflict into equation 1, the probability of a shadow factor conflict becomes:

$$P \text{ shadow factor conflict} = (1 - e^{-\lambda_2(\Delta t)}) [(1 - e^{-\lambda_1(\Delta t)}) (1 - e^{-\lambda_2(\Delta t)})] \quad 6$$

Table 4. Average Number of Left-Turn Accidents, Average Daily Traffic, and Average Critical Gaps for Eight Signalized Intersections in Indiana

<u>Intersection</u>	<u>Opposing Through ADT Per Approach (vpd)</u>	<u>Left-Turn ADT Per Approach (vpd)</u>	<u>Average No. of Left Turn Accidents</u>	<u>Average Critical Gap (seconds)</u>
US 24 x Getz Rd.	6882	995	9	5.8
US 31 x Kern Rd.	6987	862	7	5.05
US 41 x 45th St.	10330	1492	12	3.39
SR 37 x SR 252	5440	596	5	7.00
SR 37 x SR 48	3898	588	6	8.00
US 40 x Round Barn Rd.	7807	693	8	5.60
SR 67 x Franklin Rd.	15397	2347	13	2.10
US 31 x National Ave.	13747	1126	18	3.90

Application of equation 6 to four levels of major road ADT (10,000, 15,000, 20,000, 25,000) along with the corresponding left-turn ADT (1,500, 2,250, 3,000, 3,750) yielded annual number of shadow factor accidents of 0.29, 0.88, 1.37, and 1.4 accidents.

Because of the small number of shadow factor accidents, the addition of a left-turn phase does not appear to be warranted. However, an examination of the accident records indicated that two out of the twelve intersections considered in the left turn accident analysis had several accidents which should be related to the shadow factor condition; in one intersection the number of such accidents was six in one year, while in another the number was two. Because of the nature of reporting, more accidents might have occurred without being recorded as shadow factor accidents. The analysis of this particular type of accident suggests a possible countermeasure would be to caution left-turn drivers about opposing through traffic behind the opposing left turning vehicles.

Experiment 9: Amber and All-Red Phase Timing for Fixed Time Control

Amber phase indication is used after the green interval to warn motorists facing the signals to come to a stop, and if possible, to do so with safety. The duration of this phase should provide enough time for vehicles to clear the intersection before cross traffic starts to move. If the clearance interval is too long, it may be used as part of the green interval. On the other hand, short amber phase duration may constitute a hazard and increase rear-end collisions. Previous studies have shown that at high speed intersections or at exceptionally wide

streets 4 to 6-seconds of clearance interval may be warranted (8). While clearance intervals in excess of 6 seconds may be necessary at very wide or complicated intersections, they are likely to cause impatience among drivers awaiting the signal change, which may result in starting through the intersection before the green indication appears. It has been established (9) that adding an all-red interval of sufficient duration (normally 1 or 2 seconds), immediately after the amber phase, permits clearance of the intersection before cross traffic is released.

For fully actuated signal control the simulation model did not show any change in the results when the duration of the amber phase was varied and also when an all-red phase was added. However, the model proved to be sensitive to the change in amber phase and to the addition of an all-red phase for the fixed-time signal situation, as indicated by the corresponding changes in delay and conflict values. The reason for no change in the delay and conflict results of the fully-actuated control with the variation of the amber phase duration, or addition of an all-red phase probably is explained by the fact that the detection system of the computer logic terminates the green phase when there is no vehicle within the detection distance. Therefore no vehicles exist after the green phase during the subsequent amber or all-red phases. On the other hand, the amber phase occurs, in the case of fixed time, according to pretimed dials whether a vehicle exists or not after a green phase. Consequently, the results of the simulation model are sensitive to changes in amber phase timing for the fixed time control only.

Experiment 9 was designed to evaluate the effects of amber-phase duration and all-red interval on traffic performance. A fixed effect model with three independent variables was adopted. The first variable was amber phase duration which had two levels of 4 and 6 seconds. These figures were chosen because they represent the boundaries of the most satisfactory range that a good signal timing requires. The other two variables were major road volume and minor road volume. Two levels for major road volume of 1000 and 1600 vph and two levels for minor road volume of 100 and 300 vph were chosen. Three replications, 480 seconds duration time per computer run, were considered. Homogeneity and normality tests were satisfied and analysis of variance statistical test was applied. The results of the tests, shown in Tables A-28, A-29, and A-30, Appendix A, indicate that the three independent variables have no significant effect on the number of conflicts. However, the average delay per vehicle was significantly affected by major and minor road volumes at level of significance $\alpha = .05$. Also stop delay per vehicle was found to be significant for minor road volumes at the same α level. The cell means were calculated for the four major-minor volume combinations, and it was noticed that the number of conflicts for the 4 seconds amber duration was smaller than the mean for the 6 seconds amber duration. This result suggests using the lower boundary of the amber phase duration to maximize safety.

The following step was to study the effect of an all-red phase on traffic characteristics travelling through an intersection controlled by fixed-time signal. Three levels of all-red signal timing of 3, 4 and 5 seconds were assumed. The analysis was performed for a traffic

demand of 1000 vph and 100 vph of major and minor road volume, respectively. An amber phase duration of 4 seconds was assumed, and three computer run replicates were conducted for each major-minor volume combination. The one-way analysis of variance results showed that neither delay nor conflicts were significantly effected by the all-red phase duration for α level of 0.05.

The average values of the three cells of this experiment, however, showed an increasing trend in the number of conflicts with the increase in all-red phase duration. It is, therefore, suggested that the duration of an all-red phase should be kept as small as possible.

Experiment 10: Effect of Major Road Speed on Safety and Operation of Traffic

Numerous studies showed that speed enforcement, in general, reduces number of accidents but increases delay. The simulation model was used to study the effect of speed enforcement on conflicts and delay by changing the target speed of the major approaches. Two simulation runs, with 55 mph and 40 mph target speeds on the major road, were considered: and three replicated runs for each target speed were performed. The major and minor road traffic volumes, during which the two runs were implemented, were assumed to be 1200 and 150 vph, respectively. Maximum extension values of 60 and 34 seconds were adopted for major and minor phases, respectively. Averaging the three replicates of the computer outputs, a delay of 267 seconds, stop delay of 199 seconds, and 2 traffic conflicts were observed for the 55 mph target speed. These values were found to be 269, 201, and 2 for the 40 mph target speed. The difference in average and stop delay between the two cases was

in-ignificant, and there was no difference between the number of conflicts. This result was expected from this study because of the fact that the number of conflicts observed from the simulation model is detected during the amber phase, and a change in the speed of the approaching vehicle would not probably cause a significant change in the conflict occurrence.

Experiment 11: Effect of Detector Locations on Traffic Characteristics

One of the important factors in the efficient operation of isolated intersection control systems is the proper design of traffic detectors and their configuration. Although detector location and configuration should be designed on an individual intersection or control system basis, several of the standard and widely used designs should be considered.

A recent report (10) outlines six basic criteria for the setback of small area detectors when used in actuator control and they are:

1. Use sufficient setback to minimize delay to approaching vehicles.
2. Avoid long minimum greens.
3. Avoid short greens and locate detector accordingly.
4. Use a setback equal in passage time to the allowable gap.
5. Use a setback of at least 1-1/2 seconds of passage time.
6. Use sufficient setback to insure motion detection.

The variable initial interval feature has been proved to be most beneficial for locations where higher approach speeds warrant greater detector setback, the condition which exists at rural high speed inter-sections. When an actuated controller with a variable initial feature is used, detector setbacks can be increased. The minimum initial

interval will be used by the controller under conditions of light traffic. As vehicle actuations increase to a preset number, the controller automatically provides a longer initial interval up to a preset maximum. In Table 5, information is presented concerning detector setbacks at locations where actuated control with variable initial interval is used.

Volume-density controllers have not only a variable initial interval, but also have separate timing adjustments for allowable gap and passage time. These features allow a relatively low setting of allowable gap and a longer setting for passage time, a condition which makes the controller acceptable for the use of greater detector setback. Thus an early indication of vehicles approaching the intersection can be detected.

The effect of detector setback and passage time on traffic performance was evaluated by applying the simulation model. Using Table 5 as a guide for selecting detector setbacks, two passage time values of 7 and 4 seconds for major approach and 4 and 3 seconds for minor approach were studied. The results of the two simulated cases showed no difference in the number of detected conflicts as well as in stopped delay. This result is expected because at a relatively high traffic demand the change in passage time does not effect the maximum extension value; and, therefore, the controller will extend the duration of the green phase to a maximum value equal to the maximum extension.

The conclusion that can be made from this experiment is that the detectors should be located at least 400 feet from the stop bar on the major approach, and 300 feet on the minor approach for a fully-actuated controller at high speed isolated intersections, with appropriate passage times.

Table 5. Detector Setback With Use of Variable Initial Interval

(Source: Ref. 9)

<u>Approach Speed (mph)</u>	<u>With 3-Second Vehicle Interval, 4-Second Passage Time Detector Setback (ft)</u>	<u>With 3-Second Vehicle Interval, 6-Second Passage Time Detector Setback (ft)</u>
20	90 - 120	150 - 180
30	135 - 180	220 - 260
40	180 - 240	300 - 360
50	225 - 300	375 - 450
60	270 - 360	450 - 540

CONCLUSIONS

The evaluation of design and operational countermeasures at both stop-controlled and signalized divided intersections was done through the validated simulation model. The model operation was based on many assumptions which are detailed in the text. In some cases the results obtained from the simulation runs are limited by the underlying assumptions. In the following paragraphs are listed the results obtained for stop controlled intersections:

- a. The number of conflicts observed at divided intersections was found to be less than that observed at undivided intersections. In addition, the 60 foot median width indicated less number of conflicts than the 30 foot median width. The average delay per vehicle was not significantly affected by the median width.
- b. The increase of median opening size, from 24 feet to 48 feet, showed an increase in average delay per vehicle, but no significant change was observed in the number of conflicts.
- c. The provision of a right turn pocket lane at the minor road approaches, with a capacity of two vehicle, did not have any effect either for the number of conflicts or for the average delay per vehicle.
- d. Approaching the intersection on a steep downgrade of 5 percent proved to cause more conflicts than approaching on an upgrade of 5 percent.

e. The installation of a stop sign at the intersection median produced a significantly decreasing effect on number of conflicts compared with a yield sign. The increased delay observed for this case was found to be insignificant. These results particularly reflect the effect of the assumptions in the model operation; it was assumed that all vehicles fully stop at a stop sign while in reality it may not be the case.

f. The installation of advance warning systems, such as rumble strips or strobe light attached to warning signs, indicated a decrease in the number of conflicts observed at intersections; however, the average delay per vehicle was found to increase.

g. Simulation runs with different input speed limits for the minor road approaches indicated no significant effects on both safety and operation.

The results obtained from the evaluation of the sections through the application of the simulation model are listed below:

a. Average number of conflicts observed from fixed time signals and semi-actuated signals were found to be higher than those observed from fully actuated, volume density, and green extension system signals. On the other hand, the average delays of the fixed time and semi-actuated signal alternatives were significantly less than for the other three alternatives.

b. The green maximum extension of a fully actuated signal was found to have a significant effect on the number of observed conflicts; however, this factor was proved insignificant for average delay per vehicle.

c. The installation of advance warning systems at the major road approaches did not indicate any significant decrease in the number of conflicts. Also, the average delay per vehicle was not significantly affected by this variable.

d. The addition of a separate left turn phasing reduced the number of left turn conflicts, but increased the average delay per vehicle.

e. Either the increase of the amber phase duration or the all-red phase proved to increase the number of conflicts; therefore, it can be concluded that the duration of these phases should be kept at the possible minimum value. However, the simulation results indicated that adding an all-red phase caused reduction in the number of conflicts when compared to the condition of no all-red phase.

f. Simulation runs with different speed limits for the major road approaches indicated no significant effects on both safety and operation.

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Appendix A

Table A-1. Analysis of Variance Test Results for Average Delay Per Vehicle of Experiment 1

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Major Volume (A)	4	165.717	41.429	9.5783	0.00002*
Minor Volume (B)	1	65.667	65.667	15.1822	0.00036*
Median Width (C)	1	6.686	6.686	1.5459	0.2209
A X B	4	38.616	9.654	2.2320	0.0826
A X C	4	12.281	3.070	<1	
B X C	1	5.418	5.418	1.2526	0.2697
A X B X C	4	3.968	0.992	<1	
Within Error	40	173.012	4.325		
Total	59	471.366			

*Significant at α level of .05.

Table A-2. Analysis of Variance Test Results for Number of Conflicts of Experiment 1

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Major Volume (A)	4	90.122	22.530	8.5053	0.00005*
Minor Volume (B)	1	18.614	18.614	7.0271	0.01145*
Median Width (C)	1	1.879	1.879	<1	
A X B	4	11.943	2.985	1.1272	0.3574
A X C	4	22.149	5.537	2.0903	0.1000
B X C	1	.0589	.0589	<1	
A X B X C	4	34.583	8.645	3.2638	0.0208*
Within Error	40	105.959	2.649		
Total	59	285.307			

*Significant at α level of .05.

Table A-3. Analysis of Variance Test Results for Stop Delay per Vehicle of Experiment 1

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Major Volume (A)	4	148.316	37.079	9.2813	0.00002*
Minor Volume (B)	1	42.976	42.976	10.7576	0.00216*
Median Width (C)	1	4.782	4.782	1.1971	0.2804
A X B	4	31.798	7.949	1.9899	0.1145
A X C	4	14.945	3.736	<1	
B X C	1	3.465	3.465	<1	
A X B X C	4	4.741	1.185	<1	
Within Error	40	159.800	3.995		
Total	59	410.823			

*Significant at α level of .05.

Table A-4. Analysis of Variance Test Results for Delay per Vehicle-Mile of Travel of Experiment 1

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F	Significance of F
Major Volume (A)	4	0.13972	0.0349	6.6261	0.00034*
Minor Volume (B)	1	0.12696	0.12696	24.0834	0.00002*
Median Width (C)	1	0.00600	0.00600	1.1381	0.2924
A X B	4	0.03529	0.00882	1.6735	0.1751
A X C	4	0.01552	0.00388	<1	
B X C	1	0.01014	0.01014	1.9234	0.1731
A X B X C	4	0.00698	0.00174	<1	
Within Error	40	0.21087	0.00527		
Total	59	0.55148			

*Significant at α level of .05.

Table A-5. Analysis of Variance Test Results for Minor Road Delay of Experiment 1

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Volume Major (A)	4	33464.344	8366.086	21.6152	0.00001*
Volume Minor (B)	1	564.450	564.450	1.4583	0.2342
Median Width (C)	1	1686.142	1686.142	4.3564	0.0432*
A X B	4	3974.495	993.623	2.5672	0.0526
A X C	4	3266.540	816.636	2.1099	0.0974
B X C	1	1059.660	1059.660	2.7378	0.1058
A X B X C	4	2098.393	524.598	1.3553	0.2665
Within Error	40	15481.832	387.045		
Total	59	61595.856			

*Significant at α level of .05

Table A-6. Analysis of Variance Test Results for Major Road Delay of Experiment 1

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Major Volume (A)	4	8.9455	2.2363	7.0764	0.00021*
Minor Volume (B)	1	6.0929	6.0929	19.2795	0.00008*
Median Width (C)	1	0.1685	0.1685	<1	
A X B	4	1.2805	0.3201	1.0129	0.4122
A X C	4	2.8296	0.7074	2.2384	0.0819
B X C	1	0.9475	0.9475	2.9982	0.0910
A X B X C	4	0.6686	0.1671	<1	
Within Error	40	12.6412	0.3160		
Total	59	33.5106			

*Significant at α level of .05

Table A-7. Newman-Keuls Summary Results for the Significant Differences Between Means of Three Factor Interaction of Experiment 1

<u>Three Factor Interaction</u>	<u>(200x50x60)</u>	<u>(350x100x30)</u>	<u>(350x50x30)</u>	<u>(200x100x60)</u>	<u>(350x100x30)</u>
(Major Vol. x Minor Vol. x Med. Width) = (800 x 50 x 30)	5.793*	5.580*	5.307*	5.230*	4.887*
(500 x 50 x 60)	5.790*	5.577*	5.304*	5.227*	4.884*
(650 x 50 x 30)	5.320*	5.107*	4.834	4.757	4.414

*Significant at 5 percent level.

Table A-8. Analysis of Variance Test Results of Conflict Rates for the Comparison Between Divided and Undivided Intersections

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Major Volume (A)	3	0.00103	0.00034	6.257	0.002*
Minor Volume (B)	1	0.00140	0.00140	25.491	0.001*
Median Width (C)	1	0.00035	0.00035	6.382	0.017*
A X B	3	0.00057	0.00019	3.470	0.027*
A X C	3	0.00059	0.00019	3.584	0.024*
B X C	1	0.00025	0.00025	4.718	0.037*
A X B X C	3	0.00076	0.00029	4.639	0.008*
Within Error	32	0.00175	0.00005		
Total	47	0.00670			

*Significant at α level of .05.

Table A-9. Analysis of Variance Test Results for Average Delay per Vehicle of Experiment 2

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Turning Percentages (A)	2	0.5034	0.2517	<1	
Right pocket lane (B)	1	0.5600	0.5600	<1	
Median Opening (C)	1	22.6417	22.6417	8.9119	0.0064*
A X B	2	1.5270	0.7635	<1	
A X C	2	3.7486	1.8743	<1	
B X C	1	0.0568	0.0568	<1	
A X B X C	2	0.0500	0.0250	<1	
Within Error	24	60.9744	2.5406		
Total	35	90.0619			

*Significant at $\alpha = .05$.

Table A-10-Analysis of Variance Test Results for Number of Conflicts of Experiment 2

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>
Turning Percentages (A)	2	5.0555	2.5277	<1
Right Pocket Lane (B)	1	1.7777	1.7777	<1
Median Opening (C)	1	0.1111	0.1111	<1
A X B	2	3.7222	1.8611	<1
A X C	2	9.3888	4.6944	<1
B X C	1	5.4444	5.4444	<1
A X B X C	4	0.7222	0.3611	<1
Within Error	24	144.000	6.000	
Total	35	170.2219		

Table A-11. Analysis of Variance Test Results for Traffic Delay and Conflicts of Experiment 3

Case 1: Average Delay Per Vehicle (Logarithm Transformation)

<u>Source</u>	<u>DF</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>
Between Groups	4	0.1486	0.0372	<1.00
Within Groups	10	0.4473	0.0447	
Total	14			

Case 2: Stop Delay Per Vehicle (Logarithm Transformation)

<u>Source</u>	<u>DF</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance F</u>
Between Groups	4	1.0584	0.2646	1.0764	0.4181
Within Groups	10	2.4581	0.2458		
Total	14	3.5165			

Case 3: Number of Conflicts

<u>Source</u>	<u>DF</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance F</u>
Between Groups	4	124.6667	31.1687	5.9177	0.0104*
Within Groups	10	52.6667	5.2667		
Total	14	177.3334			

*Significant at α level of .05.

Table A-12. The Statistical Model for Experiment 2

Model

$$Y_{ijk} = \mu + C_i + D_j + CD_{ij} + \epsilon_{(ij)k}$$

ANOVA

(3 Replicates per cell)

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Expected Mean Square</u>
C_i	1	$\sigma^2 + 9 \phi_A$
D_j	2	$\sigma^2 + 6 \phi_B$
CD_{ij}	2	$\sigma^2 + 3 \phi_{AB}$
Within Error	12	σ^2
Total	17	

where

 C_i = control type at median $i = 1, 2$ D_j = intersection width $j = 1, 2, 3$ Y_{ijk} = estimated dependent variable: delay, conflicts, and fuel consumption $\epsilon_{(ij)k}$ = random error component σ^2 = random variance ϕ_2 = variance contributed by a fixed factor where Z = control type at median, and intersection width k = 3, number of replicates per cell μ = overall mean

Table A-13. Analysis of Variance Test Results for Average Delay per Vehicle of Experiment 4

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Control Type (C)	1	64.7142	64.7142	<1	
Intersection Width (D)	2	371.2366	185.6183	2.3449	0.1381
C X D	2	1.2890	0.6445	<1	
Within Error	12	949.8999	79.1583		
Total	17	1387.1397			

Table A-14. Analysis of Variance Test Results for Number of Conflicts of Experiment 4

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Control Type (C)	1	84.1221	84.1221	4.8223	0.04500*
Intersection Width (D)	2	13.7777	6.8888	<1	
C X D	2	19.1111	9.5555	<1	
Within Error	12	209.3333	17.4444		
Total	17	326.3442			

*Significant at level $\alpha = .05$.

Table A-15. Analysis of Variance Test Results for Number of Conflicts of Experiment 5

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Advance Warning Distance (L)	3	34.1250	11.3750	4.7894	0.0144*
Target Speed (S)	1	2.0416	2.0416	<1	
L X S	3	2.791	0.9305	<1	
Within Error	16	38.0000	2.3750		
Total	23				

*Significant at α level of .05.

Table A-16. Analysis of Variance Test Results for Number of Vehicles Exceeding Safe Speed of Experiment 5

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>
Advance Warning Distance (L)	3	3.5000	1.1666	<1
Target Speed (S)	1	24.0000	24.0000	<1
L X S	3	40.3333	13.4444	<1
Within Error	16	1304.0000	81.50000	
Total	23			

Table A-17. Analysis of Variance Test Results for Average Delay of Experiment 5

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Advance Warning Distance (L)	3	5609.8880	1869.9626	4.3320	0.0204*
Target Speed (S)	1	6.1509	6.1509	<1	
L X S	3	331.1991	110.3997	<1	
Within Error	16	6906.4988	431.6561		
Total	23				

* Significant at α level of .05.

Table A-18. Experiment 6 Cell Means, and ANOVA for Number of Conflicts and Average Delay per Vehicle

	<u>Fixed-Time Signal</u>	<u>Semi-Actuated Control</u>	<u>Fully-Actuated Control</u>	<u>Volume-Density Control</u>	<u>GES Control</u>
Number of Conflicts	7.333	16.333	2.333	3.333	3.333
Average Delay Per Vehicle	22.130	29.210	36.740	35.010	37.216

	<u>Source</u>	<u>D.F.</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F (Ratio)</u>	<u>F (Prob.)</u>
Number of Conflicts	Between	4	404.4000	101.1000	<1.00	
	Within	10	1199.3333	119.9333		
	Total	14	1603.7333			

Average Delay Per Vehicle	Between	4	491.7705	122.9426	4.911	0.019*
	Within	10	250.3385	25.0338		
	Total	14	742.1090			

*Significant at α level of .05.

Table A-19. Analysis of Variance Test Results of Average Delay per Vehicle for Experiment 7

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Major Volume (A)	2	88923.1816	44461.5908	262.5667	0.00006*
Minor Volume (B)	1	45368.7523	45368.7523	267.9239	0.00008*
Signal Timing (C)	2	212.6469	106.3234	< 1.00	
A X B	2	21467.5401	10733.7700	63.3879	0.00094*
A X C	4	1517.9363	379.4840	2.2410	0.2268
B X C	2	320.3580	160.1794	< 1.00	
Within Error	4	677.3378	169.3344		
Total	17				

*Significant at α level of .05.

Table A-20. Analysis of Variance Test Results of Number of Conflicts for Experiment 7

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Major Volume (A)	2	65.4444	32.7222	15.7066	0.01276*
Minor Volume (B)	1	8.000	8.000	3.8400	0.1216
Signal Timing (C)	2	74.7777	37.3888	17.9466	0.01005*
A X B	2	0.3333	0.1667	<1.00	
A X C	4	3.8888	0.9722	<1.00	
B X C	2	6.3333	3.1666	1.5200	0.3228
Within Error	4	8.3333	2.0833		
Total	17				

*Significant at α level of .05.

Table A-21. Analysis of Variance Test Results of Left Turn Conflicts for Experiment 7

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Major Volume (A)	2	32.4444	16.2222	<1.00	
Minor Volume (B)	1	304.2222	304.2222	16.8492	0.01480*
Signal Timing (C)	2	275.4444	137.7222	7.6276	0.0431*
A X B	2	45.7777	22.8888	1.2676	0.3746
A X C	4	50.2222	12.5555	<1.00	
B X C	2	224.7777	112.3888	6.2246	0.0591*
Within Error	4	72.2222	18.0555		
Total	17				

*Significant at α level of .05.

Table A-22. Newman-Keuls Test Results of Major-Minor Volume Interaction for Average Delay Per Vehicle of Experiment 7

Interaction Levels	(Major Vol. x Minor Vol.) (400 x 100)	(400 x 300)	(800 x 100)	(800 x 300)	(1200 x 100)
(Major Vol. x Minor Vol.) (1200 x 300)	255.110**	250.900**	248.270**	163.210**	119.020**
(1200 x 100)	136.090**	131.880**	129.250**	44.190*	
(800 x 300)	91.900**	87.690**	85.060**		
(800 x 100)	6.840	2.630			
(400 x 300)	4.210				

* Significant at 5 percent level.

**Significant at 1 percent level.

Table A-23. Newman-Keuls Test Results of Minor Volume-Signal Timing Interaction for Left Turn Conflicts of Experiment 7

Interaction Levels	(Minor Vol. x Signal Timing)			
	(100 x 2)	(100 x 1)	(300 x 1)	(100 x 3)
Minor Vol. x Signal Timing (300 x 3)	19.000*	18.334*	17.667*	17.667*
(300 x 2)	6.333	5.667	5.000	5.000
(100 x 3)	1.333	0.667	0.000	
(300 x 1)	1.333	0.667		
(100 x 1)	0.667			

*Significant at 5 percent level.

Note: Signal Timing 1: Maximum extension major = 36 seconds, Maximum extension minor = 18 seconds.

Signal Timing 2: Maximum extension major = 48 seconds, Maximum extension minor = 26 seconds.

Signal Timing 3: Maximum extension major = 60 seconds, Maximum extension minor = 34 seconds.

Table A-24. Analysis of Variance Test Results of Number of Conflicts for Experiment 8

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>
Advance Warning Distance (L)	2	3.0000	1.5000	<1.00
Number of Phases (N)	1	0.0555	0.0555	<1.00
N X L	2	0.1111	0.0555	<1.00
Within Error	12	129.3334	10.7777	
Total	17	132.5000		

Table A-25. Analysis of Variance Test Results of Number of Vehicles Exceeding Safe Speed for Experiment 8

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Advance Warning Distance (L)	2	2330.1111	1165.0555	2.3308	0.1395
Number of Phases (N)	1	150.2222	150.2222	<1.00	
N X L	2	192.1111	96.0555	<1.00	
Within Error	12	5998.0000	499.8333		
Total	17	8670.4444			

Table A-26. Analysis of Variance Test Results of Left Turn Conflicts for Experiment 8

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Advance Warning Distance (L)	2	10.7777	5.3888	< 1.00	
Number of Phases (N)	1	20.0555	20.0555	1.6484	0.2234
N X L	2	12.1111	6.0555	< 1.00	
Within Error	12	146.0000	12.1666		
Total	17	188.9443			

Table A-27. Analysis of Variance Test Results of Average Delay Per Vehicle for Experiment 8

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Advance Warning Distance (L)	2	21139.9306	10569.9653	1.1112	0.3607
Number of Phases (N)	1	2005.1333	2005.1333	<1.00	
N X L	2	2032.2195	1016.1097	<1.00	
Within Error	12	114145.8368	9512.1530		
Total	17	139323.1202			

Table A-28. Analysis of Variance Test Results of Number of Conflicts for Experiment 9

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>
Amber Duration (A)	1	3.375	3.375	<1.00
Major Volume (B)	1	1.042	1.042	<1.00
Minor Volume (C)	1	12.042	12.042	<1.00
A X B	1	1.042	1.042	<1.00
A X C	1	1.042	1.042	<1.00
B X C	1	2.042	2.042	<1.00
A X B X C	1	3.375	3.375	<1.00
Within Error	16	1698.00	106.125	
Total	23	1721.958		

Table A-29. Analysis of Variance Test Results of Average Delay Per Vehicle for Experiment 9

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Amber Duration (A)	1	9.627	9.627	<1.00	
Major Volume (B)	1	523.040	523.040	6.289	0.023*
Minor Volume (C)	1	2760.615	2760.615	33.193	0.001*
A X B	1	10.989	10.989	<1.00	
A X C	1	59.914	59.914	<1.00	
B X C	1	19.296	19.296	<1.00	
A X B X C	1	0.045	0.045	<1.00	
Within Error	16	1330.678	83.167	<1.00	
Total	23	4714.204			

*Significant at α level of .05.

Table A-30. Analysis of Variance Test Results of Stop Delay Per Vehicle for Experiment 9

<u>Source</u>	<u>Degrees of Freedom</u>	<u>Sum of Squares</u>	<u>Mean Squares</u>	<u>F</u>	<u>Significance of F</u>
Amber Duration (A)	1	35.819	35.819	<1.00	
Major Volume (B)	1	43.041	43.041	<1.00	
Minor Volume (C)	1	2222.990	2222.990	50.544	0.001*
A X B	1	8.074	8.074	<1.00	
A X C	1	46.928	46.928	<1.00	
B X C	1	20.424	20.424	<1.00	
A X B X C	1	1.927	1.927	<1.00	
Within Error	16	703.696	43.981		
Total	23	3082.899			

*Significant at α level of .05.

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